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AUTHOR(S):

Jang, HM; Muta, I; Hoshino, T; Nakamura, T; Kim, SW; Sohn, MH; Kwon, YK; Ryu, KS

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Design and Electrical Characteristics Analysis of 100 HP HTS Synchronous Motor in 21st Century Frontier Project, Korea

Hyun-Man Jang, Itsuya Muta, Tsutomu Hoshino, Taketsune Nakamura, Seog-Whan Kim, Myung-Hwan Sohn, Young-Kil Kwon, and Kang-Sik Ryu

Abstract—A 100 hp class superconducting motor in the 21st Century Frontier R&D Program of Korea has been designed. A theoretical model of high temperature superconducting (HTS) motor was presented by two-dimensional electromagnetic field analysis. The motor is composed of HTS field winding, cold damper shield, air-gap armature winding and laminated machine shield. The HTS field winding consists of racetrack type double pancake coils wound with Bi-2223 HTS tapes operated at about 30 K. The operating current of the HTS tape conductor could be determined by the magnetic field distribution calculated in the HTS field winding and the I_c - B characteristics of a practical HTS conductor, taking account of its anisotropy.

Index Terms—Frontier project, HTS superconductor, synchronous motor.

I. INTRODUCTION

SUPERCONDUCTING synchronous motors without iron core might reduce size and losses compared to conventional synchronous motors as well as superconducting generators [1], [2]. It has been thought that the superconducting motor and generator should be more competitive at large rating power than conventional machines. And HTS machines are more competitive than low temperature superconducting (LTS) machines because of higher operating temperature and higher stability of HTS conductors.

This paper describes the conceptual design of a HTS synchronous motor in the 21st Century Frontier R&D Program, Korea [3]. Conventional motors design methods are not appropriate for superconducting motors and must be completely changed to take out great advantages of the superconducting properties [4]. Accordingly, we have studied the theoretical model of HTS synchronous motors and have designed a 100 hp class motor, based on two-dimensional electromagnetic field analysis.

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H.-M. Jang, I. Muta, T. Hoshino, and T. Nakamura are with the Electrical Engineering Department, Kyoto University, Kyoto, 606-8501, Japan (e-mail: hm-jang90@hanmail.net; muta@kuee.kyoto-u.ac.jp; tk_naka@kuee.kyoto-u.ac.jp; hoshino@asl.kuee.kyoto-u.ac.jp).

S.-W. Kim is with Applied Superconductivity Lab., Korea Electrotechnology Research Institute (KERI), Changwon 28-1, Korea (e-mail: swkim@keri.re.kr).

M.-H. Sohn and Y.-K. Kwon are with Applied Superconductivity Lab., KERI, Changwon 28-1, Korea (e-mail: mhshon@keri.re.kr; ykkwon@keri.re.kr).

K. S. Ryu is with the Center for Applied Superconductivity Technology (CAST), Changwon 28-1, Korea (e-mail: ksryu@keri.re.kr).

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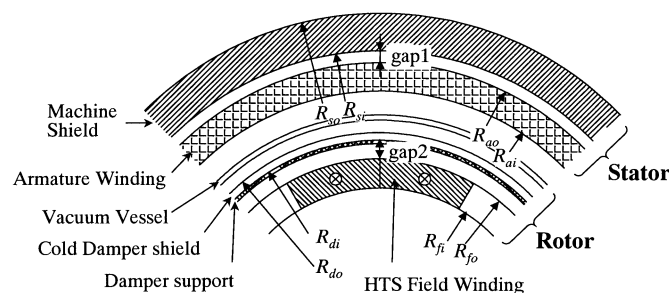


Fig. 1. Cross sectional view of HTS synchronous motor.

The motor consists of 4-pole rotating HTS field winding and stationary air-gap armature winding. A single damper system is here assumed at present because of adopting high stable HTS tape conductors to the field windings, compared with conventional LTS wires.

II. STRUCTURE OF HTS SYNCHRONOUS MOTOR

Fig. 1 shows a schematic cross sectional view of the HTS synchronous motor and illustrates the position of the principal components. In Fig. 1, the mark “ R ” illustrates the radius of each component. The motor has a nonmagnetic field core structure that rotates at synchronous speed, and an air-gap armature winding. From the central part of the cross-section, as shown in Fig. 1, a HTS field winding, a damper shield, an armature winding and a laminated machine shield are arranged toward the radial direction.

The stator consists of the Y-connected air-gap armature winding and the laminated machine shield. The armature winding is installed in the slots of nonmagnetic and nonconductive material, not only contributing to lighter weight but also removing a significant source of motor noise. Each phase winding is distributed in slots over an arc of 60 degree band. The outermost machine shield is made of laminated silicon steel for shielding the leakage flux and shaping the inner magnetic flux distribution.

The rotor consists of a 4-pole HTS field winding, cold damper shield and vacuum vessel. Each electrical arc angle θ_{wfe} of the field winding is 120 degree and the packing factor of HTS coils is assumed to be about 0.5. The HTS field winding is cooled by cryogenic gas or liquid at about 30 K.

The damper shield located between the armature and field windings, reduces the asynchronous magnetic field caused by the armature winding and acts as a thermal radiation shield.

III. THEORETICAL ANALYSIS

For the analysis of electric machine constants, a two-dimensional analysis model of the HTS synchronous motor was used, and the following assumptions are considered [4], [5].

- 1) The influence of the end winding is introduced, taking account of effective length.
- 2) The machine shield is magnetically isotropic and, the partial magnetic saturation is discarded.
- 3) The effects of the harmonic magnetic flux on the electro-magnetic shield are disregarded for the analysis of steady state characteristics.

A. Expressions for Every Inductance

1) Self-Inductance of the Armature Winding $L_a(H)$:

$$L_a = \frac{4\mu_0 l_a (k_a k_{wa} N_{at})^2}{p\pi(1-x^2)^2} D_{1p}(x) \quad (1)$$

where l_a , k_{wa} , N_{at} and p are effective axial length for calculating L_a , winding factor, armature coil turns per phase and number of pole pair, respectively. And $D_{1p}(x)$, k_a and x are given by:

$$\begin{aligned} D_{1p}(x) &= (1/4) \{1 - x^4 + 4x^4 \ln(x) \\ &\quad + (1/2)(1 - x^4)(R_{ao}/R_{si})^4\} \\ k_a &= \sin(\theta_{wae}/2)/(\theta_{wae}/2) \\ x &= R_{ai}/R_{ao} \end{aligned}$$

where θ_{wae} is electrical phase belt angle of the armature coil.

2) Self-Inductance of the Field Winding $L_f(H)$:

$$L_f = \frac{4\mu_0 l_f (k_f N_{ft})^2}{p\pi(1-y^2)^2} D_{1p}(y) \quad (2)$$

where l_f and N_{ft} are effective axial length for calculating L_f and total turns of field winding, respectively. $D_{1p}(y)$ can be expressed by substituting y ($=R_{fi}/R_{fo}$) and R_{fo} for x and R_{ao} in $D_{1p}(x)$ and k_f is given by:

$$k_f = \sin(\theta_{wfe}/2)/(\theta_{wfe}/2)$$

where θ_{wfe} is electrical pole angle of the field coil.

3) Mutual Inductance Between the Armature Windings $M_{ab}(H)$:

$$M_{ab} = -(1/2)L_a. \quad (3)$$

4) Mutual Inductance Between the Field and Armature Windings $M_{af}(H)$:

$$\begin{aligned} M_{af} &= \frac{8\mu_0 l_{af} (k_a k_{wa} N_{at})(k_f N_{ft})(1-y^{2+p})}{p\pi(1-x^2)(1-y^2)} \\ &\quad \times \left(\frac{R_{fo}}{R_{ao}}\right)^p C_{1p}(x) \quad (4) \end{aligned}$$

where $C_{1p}(x)$ is given by:

$$C_{1p}(x) = (1/4) \left\{ -\ln(x) + (1/4)(1-x^4)(R_{ao}/R_{si})^4 \right\}.$$

TABLE I
INITIAL INPUT PARAMETERS

	Rating power	75 kVA
	Terminal voltage	380 V
	Field current	45 A
	Operating temperature of field winding	30 K
	Number of poles	4
	Frequency	60 Hz
Fixed numbers	Rotation speed	1800 rpm
	Power factor	1.0
	Gap between machine shield and armature winding	10 mm
	Current density of armature conductor, J_a	3 A/mm ²
	Connection type of armature winding	Y
Variables	Synchronous reactance in p.u.	0.1 - 0.4
	Slot number	24 - 60
	Machine shield inner radius, R_{si}	0.16 - 0.23 m

B. Power Capacity

In general, the power capacity of three phase synchronous motors used to be expressed as:

$$P_a = 3V_a I_a = 3E_0 I_a (V_a/E_0) \quad (5)$$

where V_a , I_a and E_0 are phase voltage, phase current and the induced e.m.f. of the armature winding, respectively. The induced e.m.f. is

$$E_0 = \left(1/\sqrt{2}\right) \omega M_{af} I_{fo}. \quad (6)$$

And, E_0 is expressed as (7) from a vector diagram for the synchronous motors in the case of the lagging power factor

$$E_0 = V_a \sqrt{1 - 2X_d \sin \theta + X_d^2}. \quad (7)$$

From (4)–(6), the power capacity is expressed as:

$$\begin{aligned} P_a &= \frac{3\sqrt{2}\omega\mu_0 l_{af}(\theta_{wae}k_a k_{wa}\xi_a J_a)(\theta_{waf}k_f \xi_f J_f)}{p\pi} (R_{fo}R_{ao})^2 \\ &\quad \times \left(\frac{R_{fo}}{R_{ao}}\right)^p (1-y^{2+p})C_{1p}(x) \left(\frac{V_a}{E_0}\right) \quad (8) \end{aligned}$$

where ξ_a and ξ_f are packing factors of the armature and field coils, respectively. J_a and J_f are current densities for each coil.

IV. DESIGN AND RESULTS

A. Design

The basic design program consists of input parameters (fixed parameters and variables), calculation, do-loop and criterions. The input parameters and the basic design specifications of the 100 hp HTS synchronous motor are listed in Table I. The armature winding outer radius is calculated using input parameters R_{si} and gap between machine shield and armature winding, and the dimension of the armature and field windings and machine shield outer radius are calculated in consecutive.

B. Design Results

Fig. 2 shows the dependence of the estimated efficiency (excluding cooling system power) on machine shield inner radius R_{si} when the slot number is 48, taking account of copper loss,

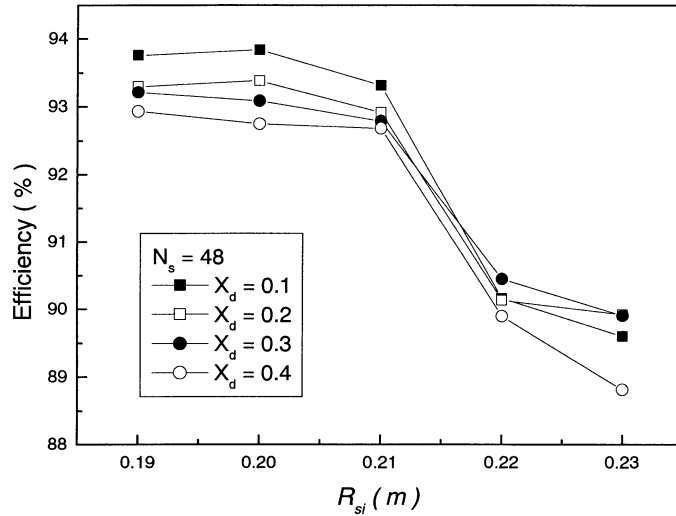


Fig. 2. Estimated efficiency vs. machine shield inner radius R_{si} when N_s is 48.

iron loss, stray load loss, eddy current loss and mechanical loss. The efficiency of the HTS synchronous motor increases with decrease of the radius. The increasing tendency in efficiency of the motor is saturated below 0.21 mm of machine shield inner radius R_{si} . The efficiency slightly decreases with increase of synchronous reactance, as shown in Fig. 2.

If the motor outer radius is decreased, the efficiency is slightly increased. However the amount of HTS conductor that is needed to construct the motor increased, as shown in Fig. 3. Therefore, the case of $R_{si} = 0.21$ m and $X_d = 0.2$ would be better to reduce the amount of expensive HTS conductor.

The several design data of 100 hp HTS synchronous motor are listed in Table II. However, it should be noted that these design data have not yet been optimized. Average flux densities in the region of the field and armature coils are about 0.6 T and 0.3 T, respectively. Fig. 4 shows a conceptual configuration of 100 hp, 4-pole HTS synchronous motor when X_d is 0.2 in the Table II. Fig. 4(a) shows a cross section and Fig. 4(b) shows a longitudinal section. The outer radius R_{so} of this machine is 238.7 mm. The effective axial straight length l_a , overall length ol_a of the armature winding and the straight length l of the racetrack field winding are 462 mm, 662 mm and 264 mm, respectively.

The stator has three phase armature windings distributed uniformly in 48 slots. For the self-starting and the speed control of the motor, the armature winding should be supplied from VVVF inverter. The armature winding is supported in nonmagnetic slots (e.g., GFRP) and cooled by air, which flows through several radial air ducts as shown in Fig. 4(b). Such armature coils are wound with rectangular type copper conductors of double layer in the slot. There are 4 coils in each layer, and they are connected in series. The number of turns of armature coil is 64 per each phase, and the rated phase current of the armature coil is about 114 A for the power capacity of 75 kW.

Each HTS field coil set consists of racetrack type 5-double pancake coils. 1150 meters of HTS tape conductor must be required to fabricate each field winding. The HTS conductor cross-section is assumed to be 0.25 mm thick and 3 mm width.

TABLE II
DESIGN DATA OF 100 HP HTS SYNCHRONOUS MOTORS IN CASE OF
DIFFERENT SYNCHRONOUS REACTANCE X_d WHEN N_s IS 48

Symbol	$X_d=0.1$	$X_d=0.2$	$X_d=0.3$	$X_d=0.4$
R_{so} (mm)	240	238.7	237.7	237
R_{si} (mm)	210	210	210	210
R_{ao} (mm)	200	200	200	200
R_{ai} (mm)	180	180	180	180
R_{so} (mm)	158.4	164.5	164.7	164.2
R_{si} (mm)	150.5	156.7	156.8	156.4
R_{fo} (mm)	140	140	140	138
R_{fi} (mm)	109.2	112	113.4	110.4
l (mm)	244	264	280	295
l_a (mm)	443	462	479	494
ol_a (mm)	642	662	678	693
ol_f (mm)	420	442	459	471
N_{at}	64	64	64	64
N_{ft}	5352	4920	4704	4784
L_a (mH)	0.958	1	1.04	1.07
L_f (H)	2.55	2.337	2.26	2.38
M_{af} (mH)	18.07	18.6	19.5	20.75
X_d' (p.u.)	0.0867	0.17	0.251	0.332
X_d'' (p.u.)	0.065	0.119	0.175	0.231
T_{do}' (s)	100	100	100	100
T_{do}'' (s)	1.5	1.5	1.5	1.5
T_d' (s)	86.65	85.211	83.75	83.08
T_d'' (s)	1.125	1.047	1.04	1.04
Specific weight (kg/kW)	3.33	3.325	3.35	3.42
Specific volume (m ³ /kW)	0.00204	0.00205	0.00208	0.0021
Efficiency (%)	93.3	92.91	92.78	92.68

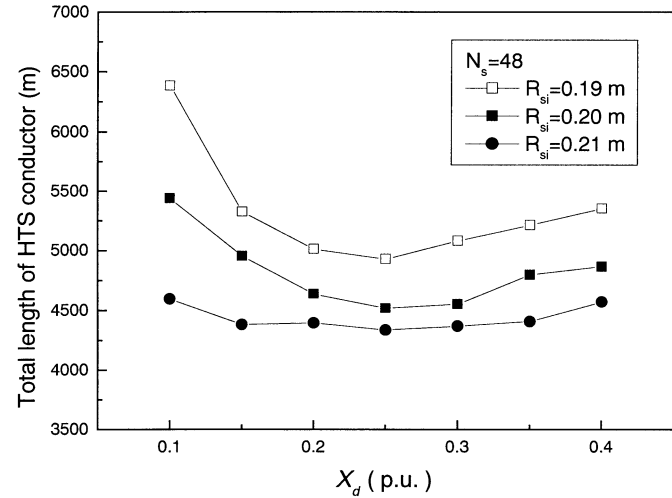


Fig. 3. Total length of HTS conductor vs. synchronous reactance X_d .

C. Operating Condition of HTS Field Winding

In the field winding, HTS coil performances related with field winding operating current versus magnetic field at the operating temperature must be desired to obtain higher efficiency motor design [6]. The critical current of Bi-2223 HTS tape is sensitive to both operating temperature and magnetic field. And, the critical current significantly depends on the perpendicular magnetic field (B_{\perp}) than parallel magnetic field (B_{\parallel}). Fig. 5 shows the critical current versus the magnetic field (I_c - B_{\perp}) curves of the Bi-2223 tapes fabricated by NST (Nordic Superconducting Technologies), and the load line of HTS field winding according to calculated magnetic field. The I_c - B_{\perp} curves were measured at the temperature of 30 and

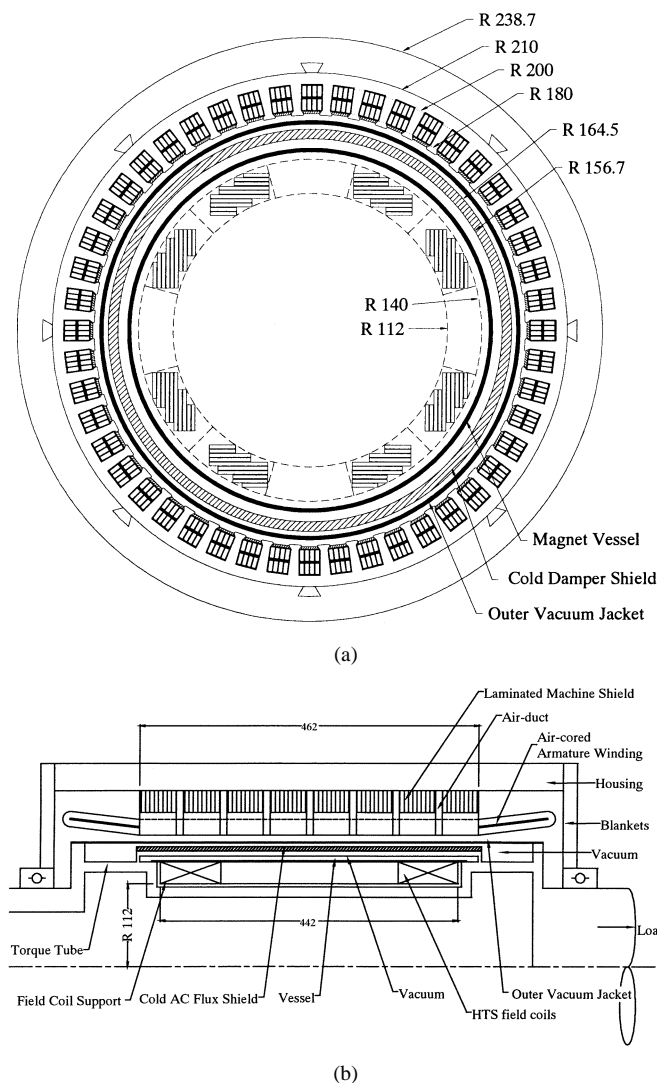


Fig. 4. Conceptual configuration of the 100 hp, 4-pole HTS synchronous motor when X_d and N_s are 0.2 and 48, respectively.

40 K at KERI. The load line is calculated using maximum values of the component of the magnetic field perpendicular to the tape surface. The critical operating current of the HTS field winding can be determined by intersection points of the load line and I_c-B_\perp curve. From Fig. 5, the critical operating current (P_c) of the HTS field winding is estimated to be 83 A when the rated operating temperature is 30 K. We used the operating current of 46 A with about 45% margin. Even though the temperature of the HTS field winding increased to 40 K, the HTS field winding has the current margin of about 30%.

V. CONCLUSION

The theoretical study and the conceptual design of HTS synchronous motor in 21st Century Frontier R&D Program of

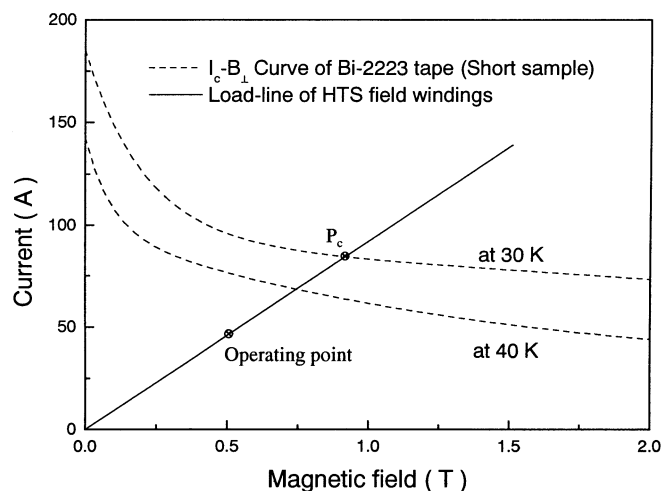


Fig. 5. Critical current vs. magnetic field of a Bi-2223 short tape at 30 K and 40 K, and load line of HTS field winding.

Korea has been done. At the first step the output power of the HTS motor is 100 hp at 1800 rpm of synchronous speed. Its final target would be the HTS motor of 3000 hp.

The motor consists of an air-gap armature winding at the stator and a Bi-2223 HTS field winding at the rotor. Each coil set of HTS field windings consists of 5 racetrack type double pancake coils, and its operating current is 46 A at about 30 K.

Several design data were introduced for the purpose of the R&D program on 100 hp HTS synchronous motor.

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